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Poster paper

Recent development in Kirkpatrick–Baez focusing systems at the ESRF

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European Synchrotron Radiation Facility (ESRF) in-house designed Kirkpatrick–Baez (KB) focusing systems have been extensively used for high efficiency beam focusing over the past years. More recently however, increasing interest in nanofocusing techniques has directed our development efforts towards more compact, higher stability designs for dynamic focusing systems in which the optimization of numerous parameters enables mirror bending approaching its mechanical limits. Simultaneously, progress in fixed focus mirror fabrication techniques – notably ion beam figuring, differential deposition and elastic emission machining – now make the fabrication of highly elliptical, fixed focus X-ray optics an interesting option. This has simplified conception (no bending mechanics) which in turn has led to the design of miniaturized KBs.

A general overview of these recent developments in both dynamic bending and fixed focus KB systems is presented.

1. History and statistics

Kirkpatrick-Baez (KB) X-ray focusing systems have been built regularly at the European Synchrotron Radiation Facility (ESRF) since 2000. The original design, based on monolithic flexure hinge mirror benders, has been developed to become a semi-standard product for optics of 170 and 300 mm length. A more compact 96 mm bender has also been added to the line up. To date, 25 KB systems based on these three bender types and 15 single-bender systems have been manufactured.

2. Bender grinding and lapping

Continual progress in the quality of flat polished X-ray optics requires increasingly tighter manufacturing tolerances on mechanics to avoid distortion of the optical face when clamped to the bending device (see figure 1). All ESRF benders are wire electrical discharge (ED) machined from pre-ground blocks. Supplementary grinding and lapping operations on the finished bender prior to mirror assembly

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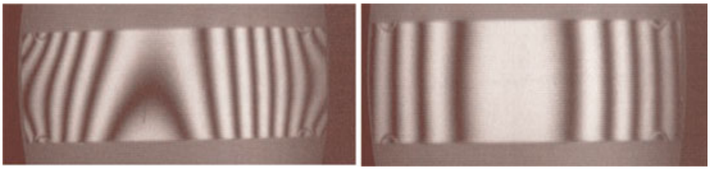

FIGURE 1. Interferogram of mirror fixed to bender – before and after lapping operation.

are mandatory to guarantee flatness and co-planarity of the reference surfaces to the highest possible accuracy. Specific tooling has been developed to ensure stress-free clamping during these operations.

3. Invar and thermal stability

First-generation ESRF mirror benders were manufactured from a precipitation hardened martensitic steel alloy with an elastic limit in excess of 1000 MPa (F16-PH from Ugine) – a stainless-steel grade well adapted for monolithic flexure-based mechanics.

For its optical polishing and thermal properties, X-ray optics are generally produced from single crystal silicon, with a coefficient of thermal expansion (CTE) of 4.5 ppm K^{-1}.

In-house experiments have shown that, as the mirror is clamped or bonded directly to the bender body, a significant gain in thermal stability performance can be obtained by using Invar alloy for the bender. Unfortunately, the mechanical properties of Invar are far from ideal for flexural-based mechanics and precautions must be taken to avoid overstressing the flexures; notably the manufacturing process, grain size and orientation of Invar blocks must be carefully controlled. A specific two-stage heat treatment is obligatory to guarantee ultimate thermal and dimensional stability.

4. Bonding

One drawback with dynamic bending systems is the loss of useful mirror length due to clamping and bending mechanics. This is most critical on short, nanofocusing KBs. To limit this drawback, the ESRF has developed a bonding technique strong enough to withstand the high bending stresses associated with strong aspheres. Mirror distortion is minimized, the optical surface is left totally clear and useful mirror length is increased.

5. Metrology and stitching

Significant progress has been made over recent years on accurate slope error measurement of strongly aspherical optics. At the ESRF, this operation is performed primarily using a deflectometry technique based on the long trace profiler in which two beams from a Michelson interferometer are reflected by the surface under test and pass through focusing and steering optics to a detector. For ultimate measurement accuracy, 'retrace' errors should be minimized. Practically this means that the angular aperture of the instrument used during measurement should be restricted as far as possible. For metrology of short radii optics, this is achieved by measuring a succession of sub-aperture profiles, tilting the optic between measurements. Results are then 'stitched' to obtain the complete mirror shape profile. This technique has improved measurement accuracy on nanofocusing mirrors.

6. Mirror profile optimization

For reflective optics the stigmatic figure for one-dimensional point-to-point focusing is the elliptical cylinder. When bending a mirror using a two moment bending device and a rectangular-shaped substrate, only an approximation of this elliptical profile can be obtained and an imbalance of the bending moments is needed.

A closer approximation is achieved by using trapezoidal-shaped substrates, giving a linear variation of the moment of inertia. However, the observed slope error remains too high when considering the strongly elliptical shapes necessary for nanofocusing.

Recently, spectacular advancements have been made in shape optimization of strong ellipsoids for dynamic benders. The complex exterior width profile of the mirror substrate is calculated using finite element analysis (FEA) methods. The complete bending system including bender, mirror, actuators and associated return springs is modelled so that the optimal substrate shape, compensating for any errors induced by the bending system, can be deduced. First experimental results show slope errors very close to predicted FEA values (see figure 2).

7. Mirror machining

To obtain such complex profiles with the required accuracy, several machining techniques for silicon have been investigated. These include diamond milling, ultrasonic erosion, and milling and wire electrical discharge machining. Wire electrical discharge machining (EDM) implies an electrically conducting workpiece, which is not the case for pure silicon. In collaboration with sub-contractors, the ESRF has optimized electrical discharge machinng (EDM) parameters for highly doped silicon substrates. After several tests, machining precision is of the order of 2 μm.

8. Compact dynamic bender

Exploiting all the above-mentioned techniques, the ESRF has developed its most compact mirror bender to date which is only 76 mm in length (see figure 3). This

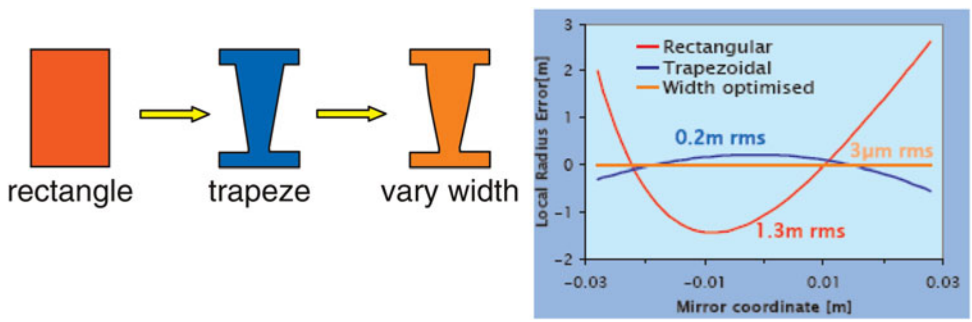

FIGURE 2. Radius error of different mirror width profiles for a bent ellipse.

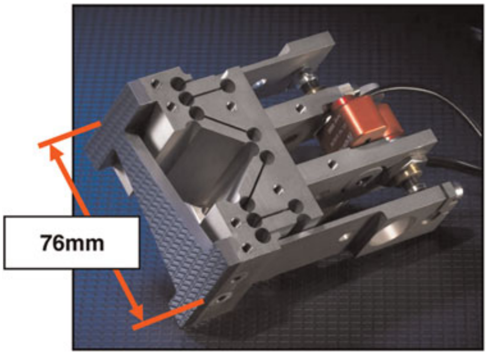

FIGURE 3. Compact dynamic bender for nanofocusing.

device is considered to be close to the ultimate feasible limit in mirror bending technology and produces a close-to-ideal elliptical shape with a downstream local radius of only 12 m. At such extreme radii, control of stress in the Si substrate becomes essential. Induced stress is proportional to Young's modulus which, for Si, varies by more than 30 % depending on crystalline plane orientation. The substrate is therefore cut according to the optimal plane for the lowest stress.

9. Fixed-focus KB systems

For stronger aspheres, fixed-focus optics obtained using ion beam figuring or differential deposition methods can be envisaged. Continual progress in fabrication now makes the fabrication of highly elliptical, fixed-focus X-ray optics an interesting option. This has simplified conception (no bending mechanics), which in turn has lead to the design of miniaturized KBs.